The Characterization of Fast Fracture and Arrest in Structural Materials

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Long, catastrophic fractures can be prevented by assuring that a crack initiated in a brittle weld, hard spot, or other low-toughness region will be arrested either by the surrounding standard quality material or by strategically placed higher toughness crack arrestors. Various methods of specifying material requirements for arrest have been proposed, such as Robertson's arrest temperature(1), Pellini's FAD(2) and K_a, stress intensity at arrest.(3-4) In general, these methods rely on static or quasi-static analyses of fracture and are approximate. Recent calculations by the authors(5) indicate that a significant part of the kinetic energy transmitted to the structure by a propagating crack is conserved, and that the kinetic energy release rate contributes to the crack driving force. The implication is that fracture arrest is influenced by the total amounts of strain and fracture energy released and dissipated by the structure throughout the propagation event, rather than by the instantaneous values of R and G at the point of arrest. Accordingly, the material property that enters into calculations of crack arrest is R, the fracture energy release rate, or the related quantity, K_d, the dynamic toughness ($K_d = \sqrt{\frac{ER}{1-\nu^2}}$, where E is Young's modulus and ν Poisson's ratio), including the variation of R (or K_d) with crack velocity.

This paper describes a testing procedure that makes it possible to initiate an unstable fracture under controlled conditions in the laboratory, to regulate velocity of the crack and the distance the fracture propagates in the test piece prior to arrest, and to measure the velocity dependence of R (and K_d). The test piece and method of loading are illustrated in Figure 1. The test piece is a DCB-test specimen, typically 12 cm wide by 30 cm long with a 10 cm long blunted slot. The unstable fracture is initiated from the slot by slow, essentially static, wedge-loading in an ordinary testing machine and propagates under conditions of constant wedge opening, with a diminishing stress field, and ultimately arrests. Since wedge loading is relatively "stiff", little energy is exchanged between the test piece and the testing machine during propagation. For this reason test results are expected to be relatively insensitive to the character of the testing machine. Wedge loading also introduces a compressive stress parallel to the crack plane which tends to stabilize the crack path. Hence, the side grooves ordinarily required to keep the crack from turning are not needed and this simplifies the analytical problem and the measurement of velocity.

A fully dynamic analysis of unstable crack propagation in the DCB-test piece has been devised which employs the beam-on-elastic foundation model illustrated in Figure 2(5). Calculations have been performed for an Euler-Bernoulli beam which accounts for translational inertia(5) and more recently for a Timoshenko beam which, in addition, accounts for shear deformation and rotational inertia. These analyses relate the velocity of the fracture and the distance propagated prior to arrest to (i) the geometry of the specimen, (ii) K_q, the stress intensity at the onset of propagation which depends on the bluntness of the starting slot and (iii) R (or K_d), which can vary with velocity. The calculations also show that the kinetic energy in the DCB specimen is substantially conserved. Accordingly, estimates of the average dynamic toughness $\bar{K}_d$ can be derived from the expression(6) $\bar{K}_d \approx \sqrt{K_q K_a}$, where

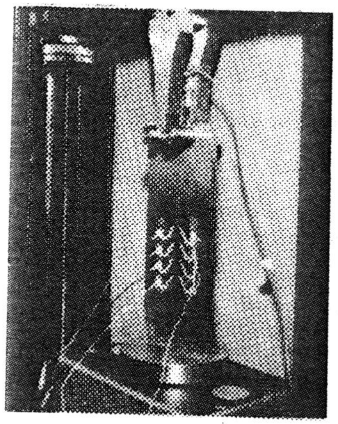
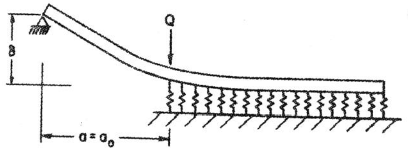
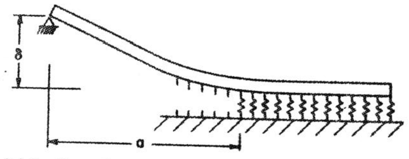


Fig. 1. Wedge-loading test arrangement



(a) Equilibrium Configuration Prior to Onset of Unstable Crack Propagation



(b) Configuration During Unstable Crack Propagation

Fig. 2. Beam-on-Elastic-Foundation Model at DCB specimen. δ is the critical wedge-opening displacement. The force Q simulates the blunt starting slot

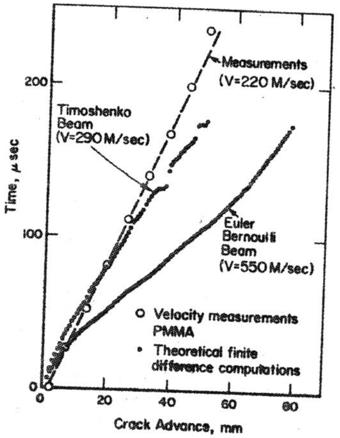


Fig. 3. Comparison between experimental crack growth-time measurements in PMMA and two theoretical calculations employing either the Euler-Bernoulli or Timoshenko elastic-beam-on-foundation model: $(E/\rho)^{1/2}$ =1608 m/sec and K_q/K_a = 1.89

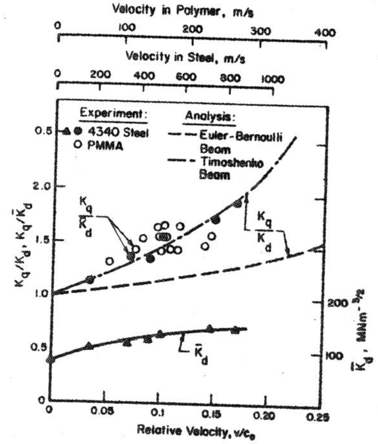


Fig. 4. Measurements and calculations of (i) the influence of K_q/K_d on steady-state velocity, and (ii) the effect of velocity on $\bar{K}_d$ for 4340 steel (yield strength: 1930 MNm^{-2}, $K_{Ic} \sim 75$ $MNm^{-3/2}$) and PMMA (yield strength: 53.9 MNm^{-2}, $K_{Ic} \sim 0.9$ $MNm^{-3/2}$)

K_a is the static stress intensity at arrest based on the wedge opening and crack length at arrest.

Test results and the analytical solutions illustrate two unusual features of the wedge-loaded-DCB test procedure:

(1) Unstable fractures propagate at essentially constant velocities in the wedge-loaded DCB-test specimen. Velocity measurements performed on 4340 steel$^{(5)}$ and the PMMA polymer$^{(7)}$ show that the unstable fractures attain a steady-state speed within millimeters of the starting slot, maintain this speed for about 75% of the distance traveled and then decelerate and arrest. The extended period of steady-state propagation is a consequence of the inertia of the beam and is consistent with predictions of the beam-on-elastic-foundation analyses. As shown in Figure 3, the velocity profile calculated with the Timoshenko analysis for a velocity independent K_d-value is in very good agreement with the measurement. As a result of the constancy of velocity, $\overline{K}_d$-values derived from DCB tests are good estimates of the K_d-value associated with the peak steady-state velocity.

(2) Although the crack speed is essentially constant throughout any one propagation event, a wide range of speeds can be produced. This is done by altering the energy stored in the specimen at the onset of propagation (altering the bluntness of the starting notch) or the geometry of the specimen. Fracture speeds in the range 200 to 1,000 meters per second have been produced in 12.5 cm x 30 cm steel specimens and higher velocities are possible in larger specimens. Figure 4 describes the velocity dependence of $\overline{K}_d$ for 4340 steel. It also illustrates that observed dependence of the steady-state crack velocity on the $\frac{K_q}{K_d}$ -ratio is in very good agreement with the Timoshenko-beam-on-elastic foundation analysis. The implication is that velocity values can be deduced simply from measurements of the critical wedge-opening displacement and the lengths of starting slot and the arrested crack.

The possibility of employing composite-DCB test specimens consisting of a low toughness "starter section" electron beam welded to the "test section" has also been demonstrated. Unstable fractures have been initiated in the starter section and injected at high speed into the test section at ambient as well as at low temperatures. The arrest capabilities of structural steels close to their transition temperature are currently being studied in this way.

Acknowledgments. The authors are grateful for the financial support provided by the Ship Structure Committee, The Army Research Office (Durham) and Battelle-Columbus and for invaluable assistance from P. Mincer, R. Barnes, and C. Pepper.

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